(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
31 May 2001 (31.05.2001)

PCT

(10) International Publication Number
WO 01/38884 A1

(51) International Patent Classification[7]: G01P 3/36, G01N 21/00

(21) International Application Number: PCT/US00/32124

(22) International Filing Date: 22 November 2000 (22.11.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

60/166,943	22 November 1999 (22.11.1999)	US
60/178,579	28 January 2000 (28.01.2000)	US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier applications:

US	60/166,943 (CON)
Filed on	22 November 1999 (22.11.1999)
US	60/178,579 (CON)
Filed on	28 January 2000 (28.01.2000)

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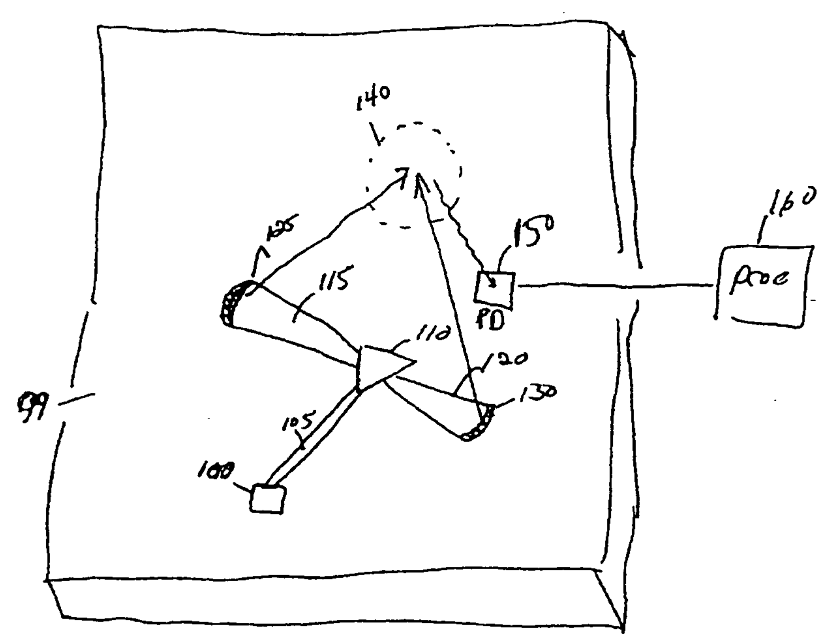
(54) Title: MICRO PHOTONIC PARTICLE SENSOR



(57) **Abstract:** A semiconductor laser diode system which detects velocity, concentration and direction of movement of moving particles. All of the parts including the laser diode (100), waveguides (105, 115, 120), beam splitter (110), output waveguides, and gratings (125, 130), are all formed on a single semiconductor substrate (99).

WO 01/38884 A1

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(81) **Designated States** *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) **Designated States** *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *With international search report.*
— *Before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments.*

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MICRO PHOTONIC PARTICLE SENSOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority from Provisional applications serial no 60/166,943, filed 11/22/99 and 60/178,579, filed 1/28/00.

STATEMENT AS TO FEDERALLY-SPONSORED RESEARCH

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (U.S.C. 202) in which the Contractor has elected to retain title.

BACKGROUND

Many different techniques are known for measuring particle velocities. Laser Doppler velocimeters are commercially available. These devices generally include a gas laser coupled with discrete optics that form relatively large and nonportable instruments. The optical systems in these instruments require beam alignment. They are prone to misalignment due to vibration and temperature changes. However, the structure in these devices has not been easily adaptable for applications that have required integrated sensors.

SUMMARY

The present application teaches a particle sensing system formed of optical microsensors. More specifically, a system is disclosed which uses a laser to produce an optical beam, the optical beam being split on a substrate, and coupled to curved gratings which form an interference pattern.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other aspects will now be described in detail with reference to the accompanying drawings, wherein:

Figure 1 shows a basic diagram of the integrated micro photonic particle sensor;

Figures 2A and 2B show exemplary waveforms in the figure 1 device;

Figures 3A and 3B show alternative systems; one using a dual, offset arrangement, and the other using a vibrator to obtain additional information;

figures 4A and 4B show representative electronic signals obtained from a photodetector;

figure 5 shows an alternative embodiment;

figure 6 shows an alternative embodiment which uses dual diodes.

DETAILED DESCRIPTION

The most basic version of the system is formed from a micro optic integrated sensor made from a solid-state laser, embedded waveguides, optical beam splitters, a curved grating, and an integrated sensor. The sensor described in the embodiment uses the well-known laser Doppler anemometry technique. This embodiment integrates all the optics into a single package. This allows the probe dimensions to be reduced, thereby further reducing associated fabrication costs. All of these parts are preferably formed on a semiconductor substrate, such as a silicon substrate.

Speeds of different particles can be measured based on the principle of the laser Doppler anemometer. Two light beams are caused to coherently interfere at a specified wavelength to form a beam volume. Particle motion at the location of the interference scatters the light. The scattered light from the particle motion is measured using a photodetector 150.

The waveform from the scattered light can be used to detect characteristics of the particle motion. The speed of the particle can be determined based on the peak-to-peak spacing of the waveform of the scattered light in the frequency or time domain.

The moving direction of the particles can be determined from the shape of the waveform. Figure 4A shows a waveform of an electronic signal produced by the photodetector for a particle moving from left to right. A particle moving from right to left is shown in Figure 4B. The envelope of these waveforms therefore indicates the direction of movement.

The basic layout of the embodiment is shown in figure 1. A substrate 99 may be a substrate formed of silicon or some other semiconductor material. The optical components are formed on the substrate. Diode 100 may be a laser diode of any specified type. The output of diode 100 is coupled to a waveguide 105 which couples the diode output to a beam splitter 110. The beam splitter 110 sends the diode output to two separate paths 115, 120. Each path culminates in a curved grating 125 and 130. These gratings are designed to reflect the laser beam to a point away from the substrate shown herein as the measuring volume 140. The fringes illuminate particles or other solid objects that traverse the fringes. Therefore, the Doppler signal obtained at the detector may be used to calculate the velocity of the moving object as $U = \frac{\delta}{\tau}$.

The interference fringe pattern at the area 140 is shown for example in figures 2A and 2B. The distance between the fringes, δ, may be calculated from optical components. A photodetector 150 receives scattered light, and may be associated with a processor such as 160, which may be on-chip or off chip, and which calculates the values from the fringes and the envelope.

The system can be used for a number of different applications including naval, aero, biomedical and industrial applications. In naval applications, the system can be used to monitor the torpedo or other speed in order to monitor and control the ship. The system can also be used to set feedback for the side forces on directional guidance. Turbulence transition or the onset of cavitation can be monitored by the system to provide more efficient control over the system. Moreover, particle size distribution as well as measurement of extreme bubble population generated by the ship's propellers or torpedo thrusters can be measured.

In the aero context, this system can be used for boundary layer monitoring including laminar to turbulent transition, shear layer oscillation over cavities, and/or vortex separation in high lift maneuverable aircraft.

The system can also be used as a particle sizing sensor in an environmental monitoring device, e.g. on a battlefield, for example.

The system also includes biomedical applications including measuring blood flow in keep tissue oxygenation monitoring. For example, this can measure microvascular blood flow. The system can also be used to diagnose victims and to evaluate tissue oxygenation during evacuation and or stabilization or resuscitation. This non-invasive system can also be used to measure retinal circulation and/or arterial blood flow.

The system can also be used for industrial applications including environmental, paper, fiber optics and railroad applications.

The basic system shown in Figure 1 may be modified according to a number of different modification techniques. A first technique shown schematically in Figure 3A uses two different elements 300, 305, offset e.g. orthogonal with one another, to obtain data about two orthogonal velocity components. There may be one or multiple photodetectors receiving the data from the measuring area 140. In this way, a two-dimensional measure of the velocity components can be obtained.

In addition, the laser can be modified to apply the

sensor to different fields. Different laser frequencies may operate more efficiently to obtain information from the different fields. For example, a specific laser wavelength may be used to obtain resonant frequencies for the specific field being measured.

Another operation shown in Figure 3B includes at least one MEMS device 350, 355 which can vibrate the diffraction gratings 125. The diffraction grating is vibrated to shift the measured frequency. By monitoring the shift in the measured frequency, directional sensitivity can be determined.

The asymmetric beam volume is produced by two grating couplers and the interference between the values obtained from those grating couplers. The signal from the photodetector is analyzed to determine information about the particles. The time or frequency interval between the spectrum parts provides the speed of the particle. The shape of the intensity envelope provides the moving direction of the particle.

Another embodiment shown in Figure 5 uses a laser diode 500 which may be a distributed feedback Bragg laser or a distributed Bragg reflector laser. An advantage of these lasers is that they may provide stable, single frequency light sources. The output of the laser diode is

coupled to waveguide 502 which provides the path to a reflecting mirror 504. Use of the beam reflector 504 may be helpful to fold the light path, so as to physically reduce the chip size. The reflector can be formed based on the total internal reflection concept.

The reflecting mirror 504 reflects the laser to a beam splitter 508 that splits the beam into two different paths 510,511. The beam splitter preferably divides the power of the light beam λ_1 one into two tapered waveguides with a specified power ratio which can be 1:1. The beam splitter can be formed by physically etching the substrate material or by any other known means. The paths are tapered waveguides configured as beam expanders. These tapered waveguides may be designed to adabiatically expand the light beam from a narrow beam into a wide beam with minimized radiation loss. The tapered waveguides 510, 511 are after the beam splitter, and collect and guide divided light beans into grating coupler 514, 516 which can be the same kind of coupler as described above. The grating couplers may all be integrated on the same chip using monolithic or hybrid techniques. The grating couplers can be focused grating couplers.

The grating couplers diffract light beam lambda one

into the targeted beam volume at the desired space location. This focal point may be the whist of the Gaussian beam having planar wave characteristics. Beam size at this space may be inversely proportional to the size of the grating coupler. Because of this relationship, a large grating coupler might be desired to obtain a small beam size at that space. The grating couplers can be designed by either computer-generated holograms or by a curved and chirped grating array.

The grating couplers can also be formed by changing the index of refraction of the patterned substrate area within the couplers. They can be done by physically etching the substrate material, or by a photoinduced index change. Any beam shape at the desired space position can be obtained via the computer-generated hologram technique. The grating pattern of the computer-generated holograms can be calculated using a Fourier transform of the desired beam shape at the spaced position.

The light beams λ1 that are refracted from the grating couplers cross each other at the beam volume 530. Upon crossing, the light beams form an interference pattern. The envelope of this pattern is asymmetric, as described above. When the particle moves through the

beam volume, the light is scattered to photodetector 538 which produces an output signal indicative of the scattered light. A narrow band pass wavelength filter may be either integrated or discretely mounted to the photodetector. This passes only λ1 to the photodetector in order to reduce noise and crosstalk from other light wavelengths. By analyzing the frequency of the Doppler burst from the photodetector 538, the particle speed can be determined.

In another embodiment shown in figure 6, a second laser source 610 may be used in addition to the first laser 500. The dual lasers can use the principle of IMAX to further measure the particle size. The principle of IMAX is described in Hess, Nonintrusive optical single particle counter for measuring the size and velocity of droplets in a spray, Applied Optics, volume 23 No. 23 (1984).

Each laser can be a distributed feedback bragg laser. A second photodetector 620 is also provided to receive scattered light. Each of the photodetectors includes an integrated wavelength band pass filter.

In operation, the lasers provide light sources which have different wavelengths λ1 and λ2. The wavelength of λ1 is used to measure the particle speed and moving

direction. The wavelength of $\lambda 2$ is used to measure the particle size. A wavelength division multiplexing coupler 612 combines the light sources of the different wavelengths into the single waveguide channel 613. The beam reflector 504 reflects both frequencies $\lambda 1$ and $\lambda 2$ to the beam splitter which operates as described with reference to the Figure 5 embodiment. The grating coupler diffracts the light with wavelength $\lambda 2$ into the same targeted beam volume as $\lambda 1$. The beam size of $\lambda 2$ may be larger than $\lambda 1$, but all are diffacted into the same beam volume.

When the particle moves through the beam volume, all of the light is scattered to the first and second photodetectors 538 and 620. The wavelength filters allow light $\lambda 1$ to be received by the first photodetector 538; and light from $\lambda 2$ to pass to the second photodetector 620.

The frequency of the Doppler burst from the first photodetector 538 can be used to ascertain the speed of the particle. The scattered light intensity from the second photodetector 620 can be used to measure the particle size. Particle concentration can be calculated from the particle speed and the given measuring volume.

A spread spectrum technique can also be used by

broadband modulating the laser sources using a coded electronic pattern. At the receiver, the broadband electronic signal may be used with a narrow band filter and decode technique.

This technique can also be used to make a three-dimensional measurement using three such devices which are all on the same chip.

In this embodiment, the sensor can be made using any semiconductor material such as S, SiC, SiN, silicon-on-insulator, InP and GaAs; $LiNbO_3$ or $TaNbO_3$ based substrate. The system can also use a base made of polymer or silicon or glass materials.

Although only a few embodiments have been disclosed in detail above, other modifications are possible.

WHAT IS CLAIMED IS:

1. An apparatus, comprising:

a substrate;

a diode, formed on said substrate, and producing an output diode beam;

a waveguide, coupled to receive said output diode beam;

a beam splitter, coupled to said waveguide, to receive said output diode beam therefrom, and to split said output diode beam into first and second paths;

first and second gratings, respectively connected to said first and second paths, receiving the split diode beam from said first and second paths and distracting said first diode beam to a measuring volume in a way that causes an interference fringe at said measuring volume; and

a photodetector, also coupled to said substrate, and receiving scattered light from said interference fringe in said measuring volume.

2. An apparatus as in claim 1, further comprising a processor, receiving an output signal from said photodetector, and processing said output signal to

determine information about particles in said measuring volume.

3. An apparatus as in claim 2, wherein said processor processes said signal to determine distance between fringes of said signal to determine a velocity of particles in said measuring volume.

4. An apparatus as in claim 2, wherein said processor processes said signal to determine envelope of said signal to determine a direction of movement of particles in said measuring volume.

5. An apparatus as in claim 1, wherein said first and second paths have a substantially expanding shape, having a smallest size near said beam splitter, and an enlarged size at said curved grating.

6. An apparatus as in claim 1, further comprising a second diode, waveguide beam splitter and third and fourth gratings, arranged on said substrate, but offset from said diode, waveguide and beam splitter, and receiving information indicative of another parameter of particle motion.

7. An apparatus as in claim 1 further comprising a vibrating element, vibrating at least one of said gratings.

8. An apparatus as in claim 1, wherein said diode is a Bragg diode.

9. An apparatus as in claim 1, further comprising a path changing element, within said waveguide, folding a light path.

10. An apparatus as in claim 1, wherein said path changing element is a reflector which folds a light path between said diode and said beam splitter.

11. An apparatus as in claim 1,further comprising tapered waveguides forming said first and second paths.

12. An apparatus as in claim 1,wherein said first and second gratings produce output beams in the form of a Gaussian, and wherein said measuring volume is at a whist of said Gaussian.

13. An apparatus as in claim 1, further comprising a wavelength filter, associated with said photodetector, allowing said photodetector to receive only a single wavelength of light.

14. An apparatus as in claim six, wherein said second diode operates at a second wavelength which is different from a first operating wavelength of said first diode.

15. An apparatus as in claim 14, further comprising a second photodetector, arranged to receive scattered light.

16. An apparatus as in claim 15, further comprising a first wavelength filter associated with said photodetector, and allowing said first operating wavelength to pass, and a second wavelength filter, associated with said second photodetector, allowing said second wavelength to pass.

17. An apparatus as in claim 16, further comprising a processor, receiving outputs from said photodetector and said second photodetector, and using one of said

outputs to determine particle size, and another an output to determine another parameter about said particles.

18. An apparatus as in claim 17, wherein said another parameter is particle concentration.

19. A method, comprising:

Producing a diode light beam on a semiconductor substrate;

splitting said diode light beam into first and second parts;

using curved gratings to diffract said first and second parts to a measuring volume;

receiving scattered light from said measuring volume, using a photodetector and element that is on said semiconductor substrate; and

determining information about particles in said measuring volume based on said scattered light.

20. A method as in claim 19, wherein said information includes particle speed.

21. A method as in claim 19 wherein said information includes particle concentration.

22. A method as in claim 19, further comprising processing an envelope of a received waveform to determine a direction of movement of particles.

23. A method as in claim 19, further comprising receiving second information indicative of a second components of movement of particles.

24. A method as in claim 19, wherein said processing comprises determining laser diode velocimetry.

25. An apparatus, comprising:

a substrate, formed a semiconductor material;

a diode, formed on said substrate, and producing and output beam;

a beam splitter, formed on said substrate, and coupled to receive said output beam, and to split said output beam into first and second parts;

first and second tapered waveguides, formed on said substrate, said first tapered waveguides located to receive said first part from said beam splitter, and said second tapered waveguides located to receive said second part from said beam splitter;

first and second curved gratings, formed on said substrate, coupled to respectively ends of said first and second tapered waveguides which are distant from said beam splitter, each of said gratings producing a specified waveform at a specified measuring volume in space;

a photodetector, formed on said substrate, receiving scattered light produced from said specified measuring volume; and

a processor, processing a signal from said photo detector to process information from said scattered light.

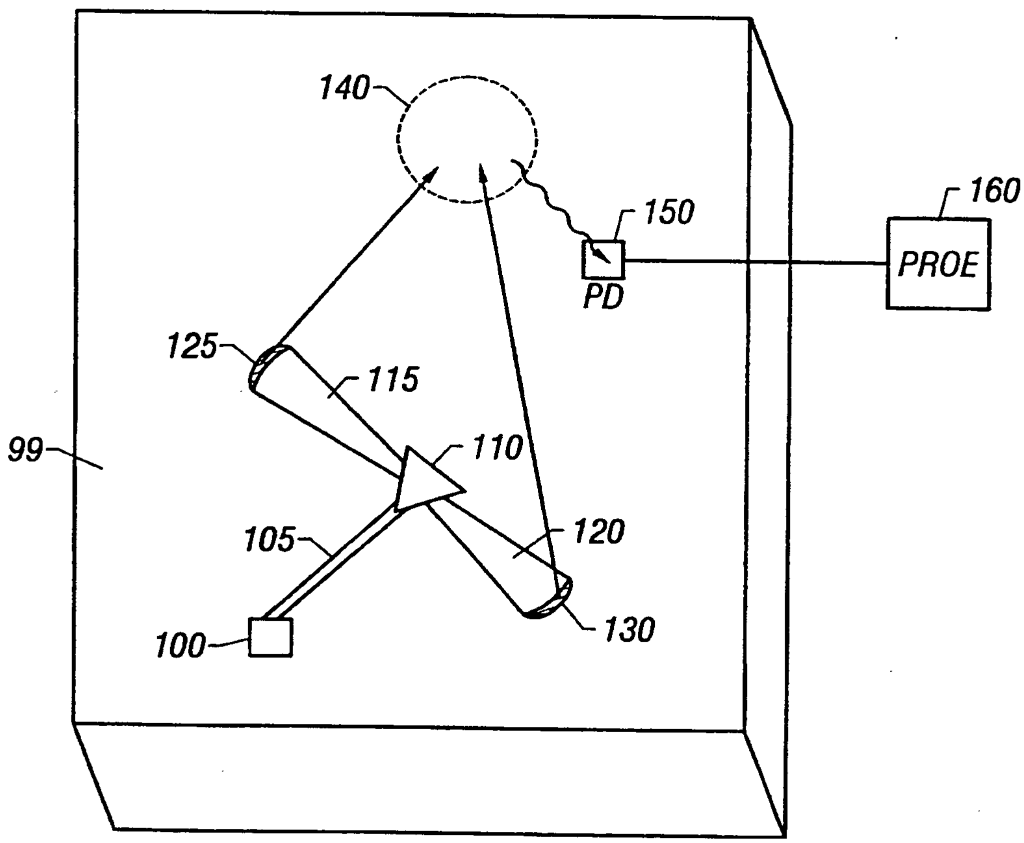


FIG. 1

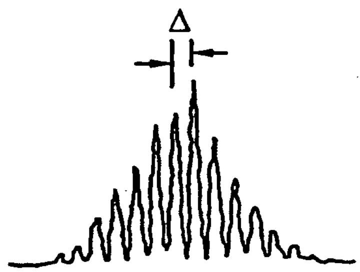


FIG. 2A

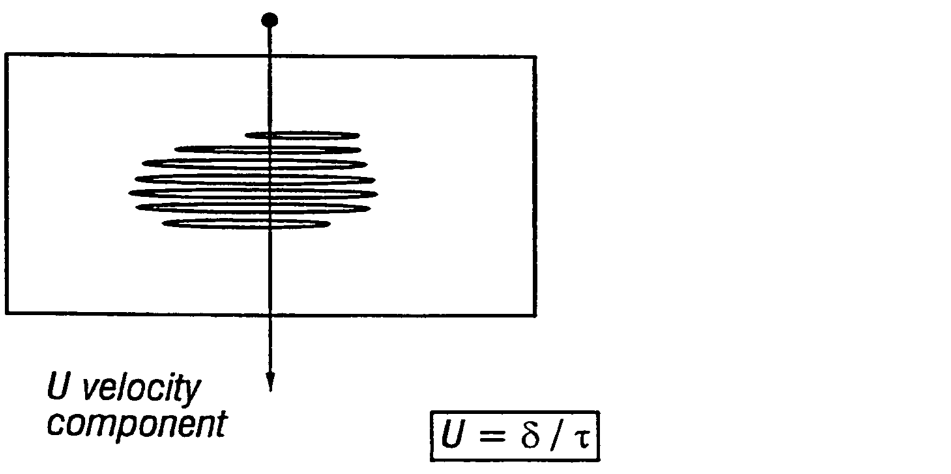


FIG. 2B

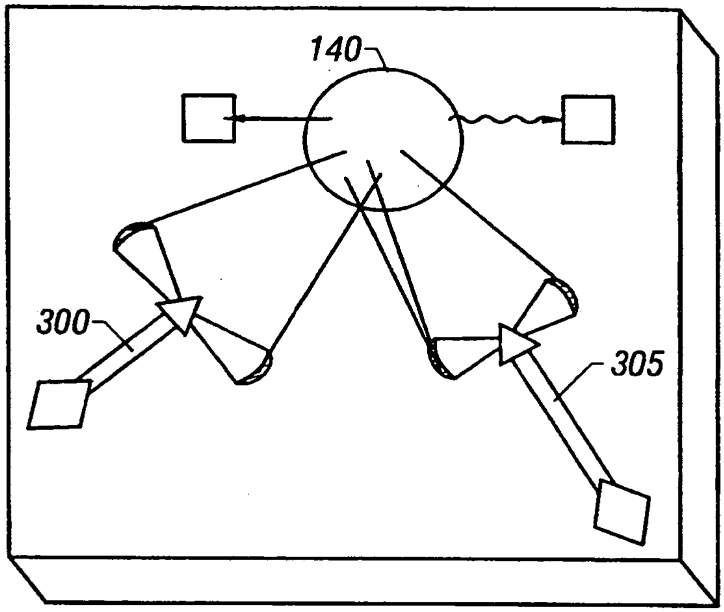


FIG. 3A

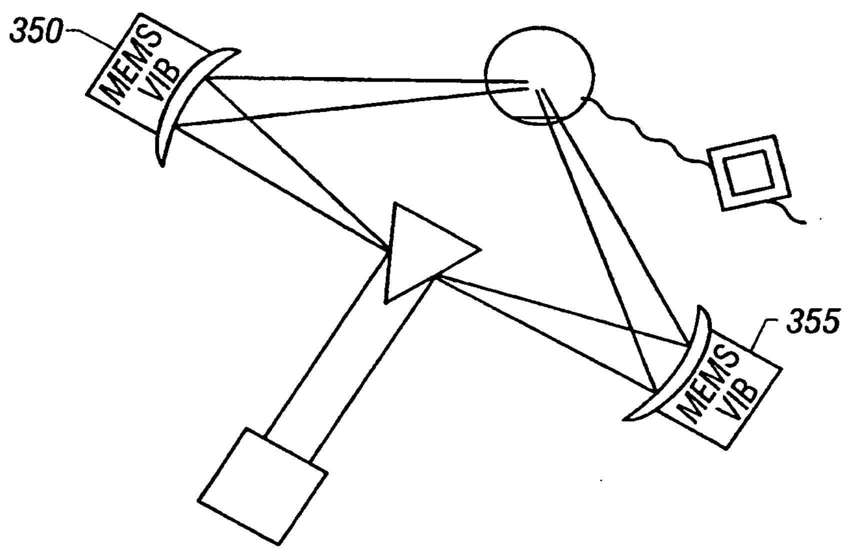


FIG. 3B

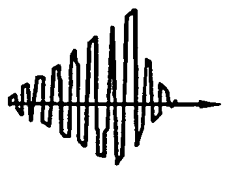


FIG. 4A

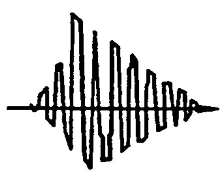
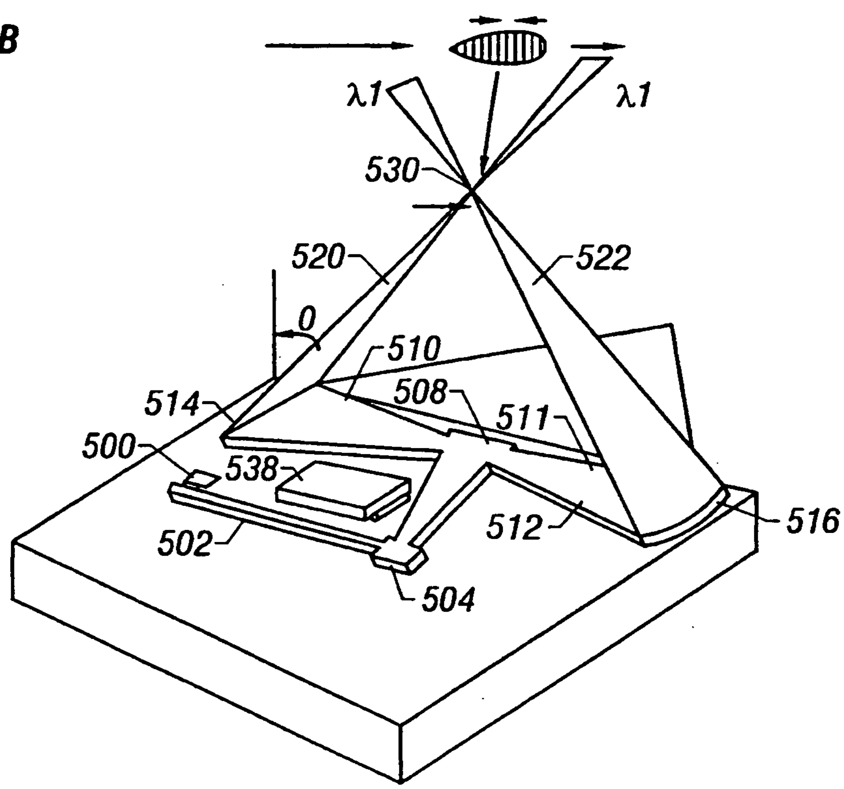


FIG. 4B



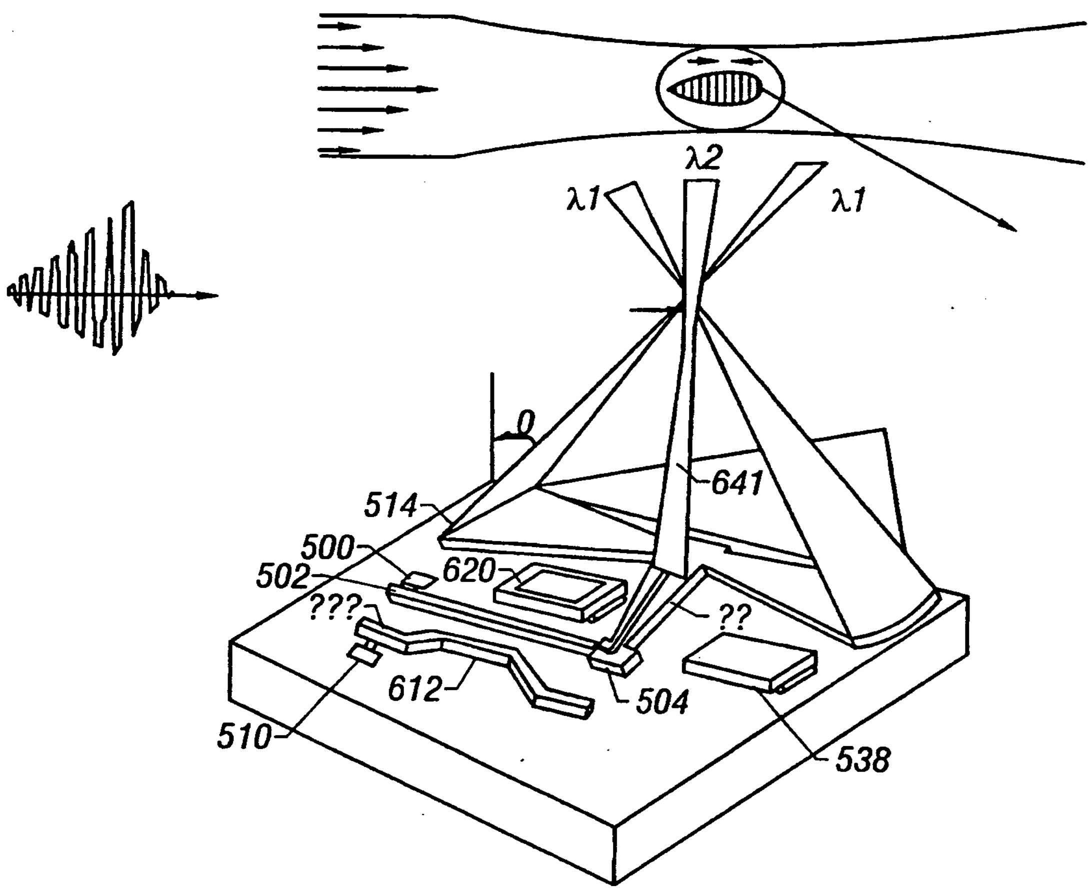


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/32124

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) :G01P 3/36; G01N 21/00
US CL :356/28.5, 342, 343
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 356/28.5, 342, 343

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
BRS-EAST

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,978,073 A (BENECH ET AL) 2 November 1999. Note integrated optics on substrate 12 and curved mirrors 30, 31.	1-25
Y	US 5,926,276 A (TAKAMIYA ET AL) 20 July 1999. Note grating splitter 10.	1-25
A	US 4,330,175 A (FUJII ET AL) 18 May 1982.	19-25
Y	US 4,140,362 A (TIEN) 20 February 1979. Note curved diffaction gratings in Fig. 2A.	19-25
A	US 4,506,979 A (ROGERS) 26 March 1985.	1-25
A	US 5,682,236 A (TROLINGER ET AL) 28 October 1997.	1-25

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
31 JANUARY 2001	01 MAY 2001

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